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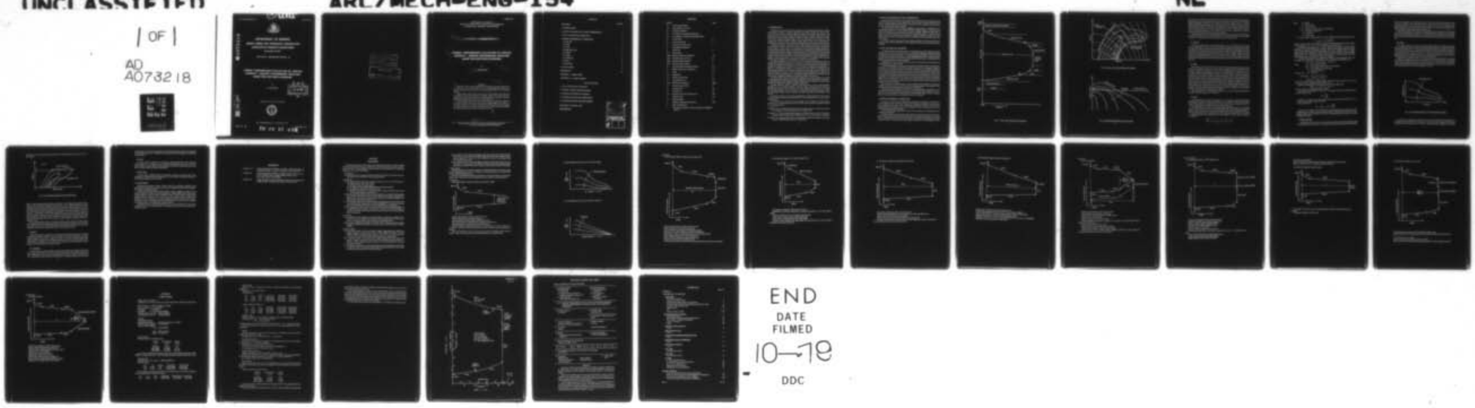

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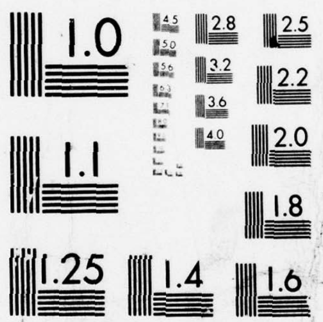

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MECHANICAL ENGINEERING REPORT 154

COMBAT PERFORMANCE EVALUATION OF FIGHTER AIRCRAFT — MISSION PERFORMANCE ANALYSIS USING FUEL-DISTANCE DIAGRAMS

by

A. RUNACRES

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(6) # COMBAT PERFORMANCE EVALUATION OF FIGHTER AIRCRAFT — MISSION PERFORMANCE ANALYSIS USING FUEL-DISTANCE DIAGRAMS

by

(10) A. RUNACRES (12) 33p.

(11) Nov 78

SUMMARY

Comparative studies of aircraft performance, undertaken to assess the relative merits of similar types, will necessarily entail not only a detailed qualitative assessment of dynamic performance but also a measure of each machine's ability to carry out specific missions.

Energy manoeuvrability theory can be used to provide specific excess power and turn capability of an aircraft throughout its operating envelope. The various manoeuvres comprising a complete mission can then be optimized from this data and a convenient graphical method employed to analyse the mission performance.

In this technique each leg of a sortie is represented on a Fuel-Distance diagram as fuel weight consumed versus range traversed. The resulting diagram serves both as a convenient illustration of the relative contribution of each leg to the total fuel consumed and range traversed over a complete mission, and also as a simple method of determining the total operational radius of action or duration on station.

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NOTATION

Symbol		Units
C_D	Aircraft drag coefficient.	
C_{DO}	Drag coefficient at zero lift.	
C_L	Aircraft lift coefficient.	
$\overline{C_L}$	Lift coefficient at optimum lift/drag ratio.	
$C_L{}^*$	Lift coefficient corresponding to minimum drag.	
D	Aircraft drag.	N
E_s	Aircraft energy state.	m
G	Load factor—number of 'g's	
K	Lift dependent drag factor.	
L	Aircraft lift.	N
M	Mach number.	
MMP	Maximum manoeuvre persistence.	rev's
MR_L	Maximum range—low level.	m
MR_H	Maximum range—high level.	m
MT_I	Maximum time on station.	s
P_a	Sea level standard atmospheric pressure.	Pa
P_s	Specific excess power or energy rate.	m/s
R	Range.	m
$R.F.$	Range factor.	m
R_{SI}	Specific intercept range.	m
S	Wing reference area.	m^2
$S.F.C.$	Specific fuel consumption.	kg/N.s
Th	Propulsion system thrust.	N
V	Aircraft velocity.	m/s
W	Aircraft mass.	kg
Wf	Propulsion system fuel mass flow rate.	kg/s
a	Speed of sound.	m/s
hs	Specified altitude.	m
g	Standard acceleration due to gravity.	m/s^2
γ	Ratio of specific heats.	
δ	Ratio of local pressure to sea level standard day atmospheric pressure.	

1. INTRODUCTION

The selection of an aircraft type by a customer involves a detailed assessment of a number of contenders in relation to a specific requirement. The range of aircraft from which a choice has to be made will often comprise machines designed to fulfil specific roles suitable to the requirements of other customers whose needs may be similar to but which differ in some significant areas from those under consideration. Where an aircraft is designed to perform a number of roles each requiring specialised design criteria the performance in some areas has to be compromised in order to achieve minimum required ability in others. The customer then has the problem of assessing the relative ability of competing designs to perform his specified tasks.

To facilitate this task it is necessary firstly to reduce the number of options to a minimum by rejecting those designs which do not meet certain minimum performance requirements; such as 'range' or 'time on station'. The performance of the remaining contenders then needs to be compared quantitatively and this may be achieved by utilising energy manoeuvrability theory to construct plots of specific energy and specific excess power for each aircraft. These quantities can be computed from a knowledge of an aircraft's aerodynamic and propulsion characteristics supplied by the manufacturer and the resulting diagrams enable the various components comprising a mission such as climb, cruise, loiter and combat to be optimized. These optimized legs can then be integrated to give a measure of complete sortie performance.

The Royal Australian Air Force (R.A.A.F.) as an operator and potential customer of modern high performance aircraft has a vital interest in such performance comparisons. The Aeronautical Research Laboratories has therefore developed computer assisted techniques to evaluate the performance of aircraft over a wide range of weapon/store configurations. In reference 1 the background leading to the performance studies involved is described and the basic theories employed in the analytical techniques and computer programs developed are outlined. Reference 2 describes a suite of computer programs designed for the major portion of the study, namely the production of energy manoeuvrability diagrams showing specific excess power and turn capability throughout the operating envelope of an aircraft.

The study extends further to specific mission capabilities of aircraft configured in a number of roles, these being air superiority, air defence, interdiction, close air support and reconnaissance. A comprehensive analytical treatment of these missions requires the handling of a great deal of data and the application of complex optimisation techniques.

However where the number of missions requiring analysis is small a simple graphical procedure can be conveniently employed. In this the various components of each mission are represented as plots on a grid of aircraft mass versus range and constructed so as to enable the total range capability or time on station to be determined. The resulting diagram, known as a fuel-distance diagram (Ref. 3), illustrates the relative contribution of each leg to a total mission.

This report describes the construction and application of these diagrams with some reference to sample mission requirements; the performance of a typical fighter aircraft is used as an illustrative example.

The S.I. system of units has been used throughout but in deference to present practice in the R.A.A.F. Imperial equivalents have been stated in brackets after the parameters referred to in Appendices 1 and 2.

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(1) Bird, D. A. H. 'Combat Performance Evaluation of Fighter Aircraft—Principles and Analytical Techniques'. A.R.L./M.E. Report No. 152 October 1978.

(2) Kipp, G. W. 'Combat Performance Evaluation of Fighter Aircraft—A Suite of Fortran IV Programs based on Energy Manoeuvrability Theory'. A.R.L./M.E. Report to be published.

(3) Page, R. K. 'Range and Radius of Action Performance Prediction for Transport and Combat Aircraft'. AGARD Lecture series No. 56 April 1972.

2. RANGE AND RADIUS-OF-ACTION PERFORMANCE

Range and radius of action are both measures of an aircraft's ability to accomplish a specific mission. A mission may be simply a requirement to fly from base to a target area, where stores must be dropped, and then to return home, or the aircraft may be required to spend some time on patrol at a specified distance from base.

The determination of the endurance capabilities of an aircraft are complicated by the disproportionate quantities of fuel consumed during the different phases of a mission such as climb, cruise, loiter etc. For civil aircraft the problem is relatively simple since apart from the take off and landing segments the major part of a typical flight consists of optimized cruise. Military aircraft on the other hand are required to perform 'combat' or 'target area attack' phases which may consume a greater proportion of fuel than that used during the outward and return cruises.

Each leg of a mission must therefore be accurately analysed so that the individual contributions to range and fuel consumption can be integrated to give the total operational range or endurance.

3. FUEL AND DISTANCE DIAGRAMS

Any flight mission may be broken down into component legs, each comprising a specific manoeuvre, such as take off, climb, cruise etc., and these can be separately analyzed employing the appropriate criteria for optimisation. A convenient graphical procedure can then be utilized to arrive at the total operational range or duration eliminating the need for a complex analytical treatment. The total mass of the aircraft is plotted against distance flown, outward flight from base considered positive and return as negative.

A diagram like Figure 1 would result. The various curves represent the individual legs the slopes being equal to 1/specific range.

A typical starting point for a sortie would be with a fully fuelled aircraft at commencement of the taxi run. The progressive reduction in aircraft mass due to fuel consumption during the various legs of the mission can then be computed and plotted on the diagram sequentially. From a knowledge of the desired fuel state on return to base the return leg can be constructed on the diagram producing a wedge shape bounded by the outward and return profiles. Then, for example, fuel consumption during the descent, attack and re-climb phases of a sortie can be computed at an estimated radius from base and the resulting curves fitted into the graphical wedge such that the end points of the descent and climb out phases coincide with the cruise curves (points A and B of Fig. 1). Some iteration involving the estimate of mission radius may be necessary to effect the desired fit.

Time on station at a specified radius is readily obtained from the diagram by equating the available mass loss at that radius, obtained from the graphical wedge, to the quantity of fuel consumed and mass of weapons delivered during loiter and combat.

This type of diagram therefore serves both as a convenient graphical presentation of the relationship between fuel consumed and range traversed during the various segments of a sortie, and also as a simple method of determining the total operational radius of action or duration after the separate component leg contributions have been computed.

4. MISSION PERFORMANCE PREDICTION

In appendix I typical mission performance requirements are described with reference to various recognized roles, these being air superiority, air defence, interdiction, close air support and reconnaissance. The form of the corresponding fuel-distance diagrams is illustrated and accompanying notes summarise both the data required for their construction and also the derived mission performance parameters.

A numerical example giving the close air support mission radius for a typical fighter aircraft is detailed in appendix II.

The data required for aircraft performance prediction can be grouped into two main categories, airframe characteristics and engine characteristics. The airframe characteristics comprise the mass, lift-drag polars and fuel carrying capacity. The propulsion characteristics comprise thrust and fuel flow variations with forward speed and altitude as well as dependence of fuel

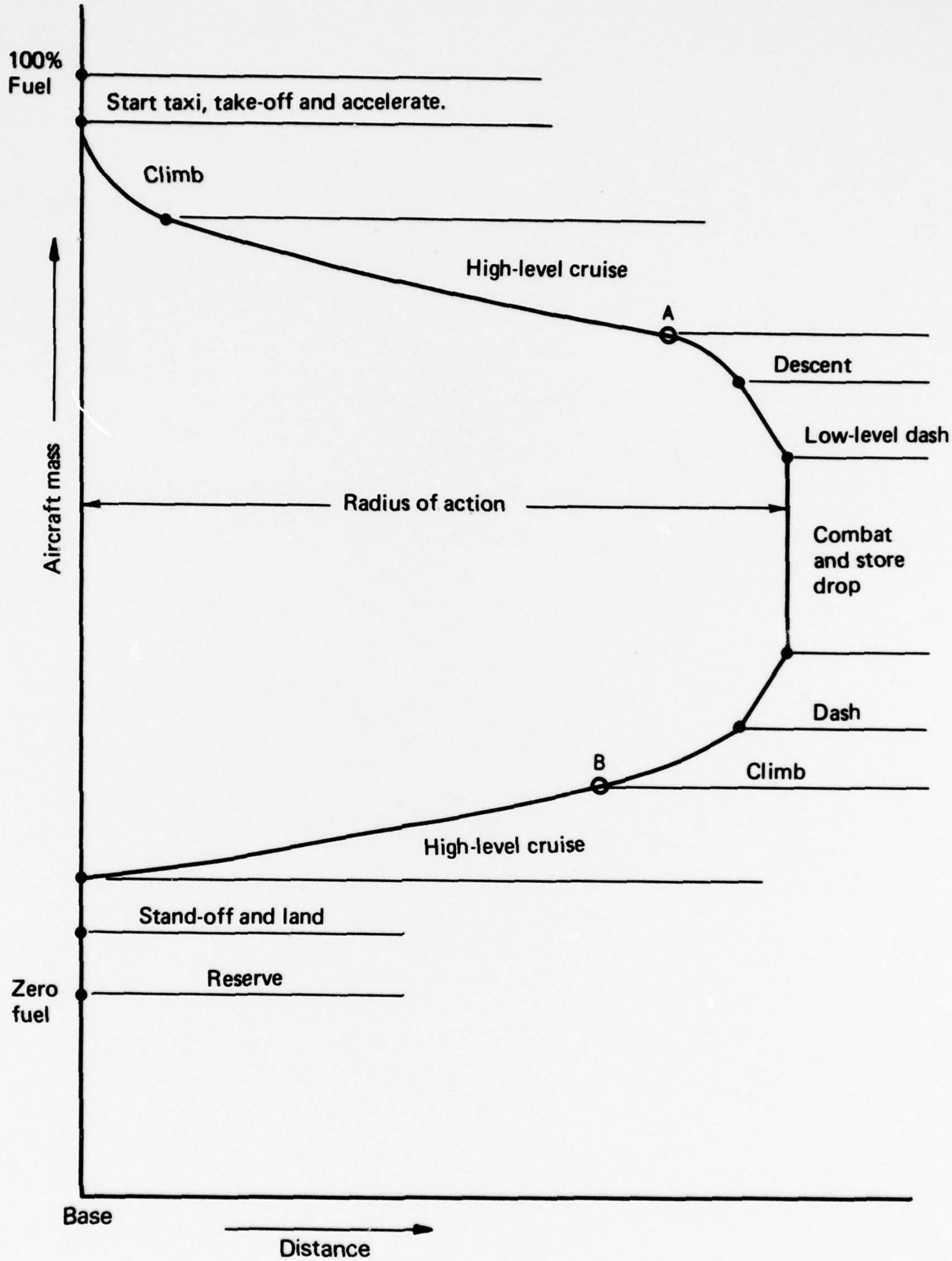

FIG. 1. FUEL AND DISTANCE DIAGRAM

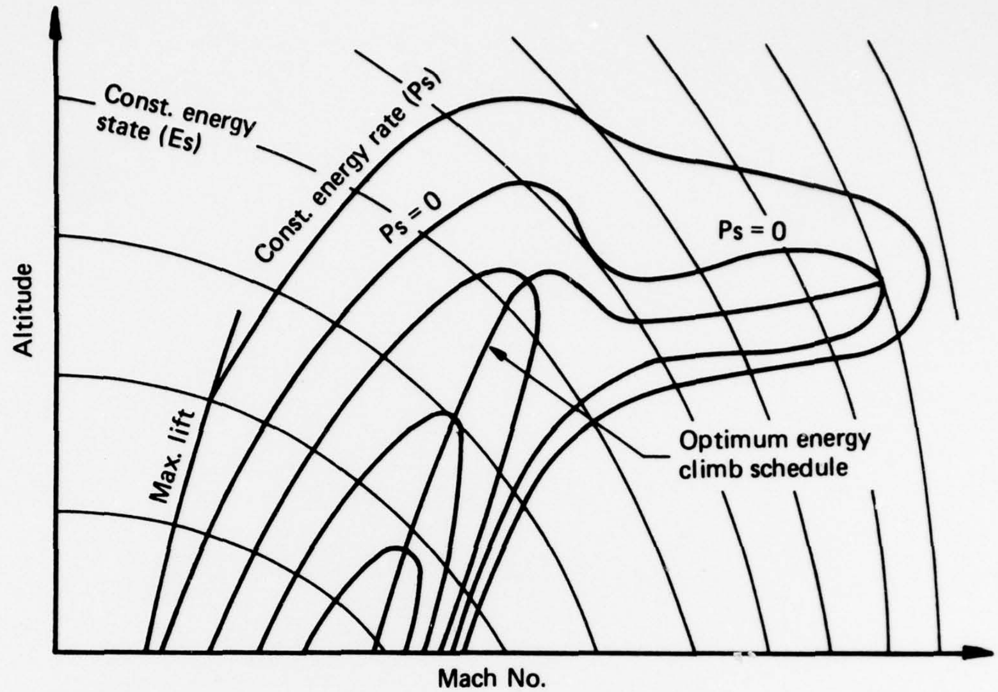

FIG. 2. SPECIFIC EXCESS POWER DIAGRAM

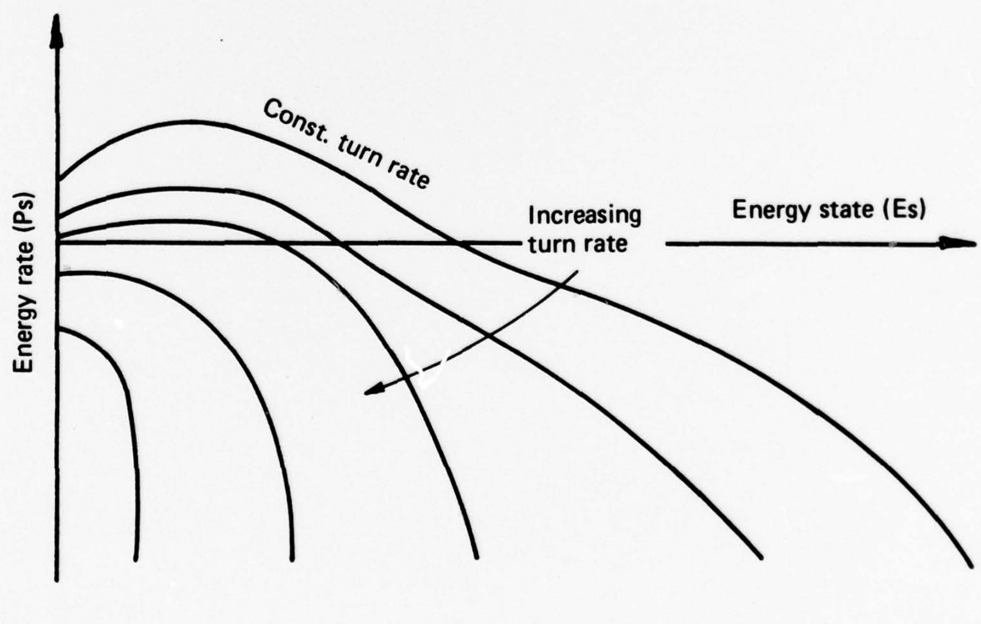

FIG. 3. MAXIMUM MANOEUVRE DIAGRAM

flow on thrust at constant speed and altitude. This type of data will normally be supplied by a manufacturer as part of his response to a customer's request for proposals to fulfil an intended purchase requirement. The data can be conveniently handled by a digital computer to quantify energy manoeuvrability throughout the aircraft operating envelope and for the aircraft configurations of particular interest to the customer. Examples of the type of diagrams produced in this way are shown in Figures 2 and 3 and a detailed description of the computational procedures involved is described in reference 2. The various types of manoeuvre comprising a sortie can then be analyzed and plotted on the fuel-distance diagram.

A brief discussion of various typical leg types follows with some reference to the calculation procedures involved and to how the results appear on the fuel-distance diagram. More detailed coverage of aircraft performance is dealt with extensively in standard texts.

4.1 Take Off.

The normal starting point of any mission analysis is with a fully fuelled aircraft. Except for very detailed analysis of aircraft take off performance the fuel consumed during the ground taxi and take off phase is taken directly from the aircraft manufacturer's specifications in which a fuel increment is usually quoted as a function of all up weight. The take off phase is normally considered to include the initial climb and acceleration to 300 m (1000 ft) altitude. The range covered will be insignificant except where the carriage of heavy or large (i.e. high drag) stores results in a long take off run and climb out. Except in such cases the take off segment of a mission will therefore be represented on the fuel-distance diagram by a small vertical line on the aircraft mass axis.

4.2 Climb.

Unless otherwise specified the desired cruise height will be that required for optimum range and this will normally be such as to require a fairly prolonged climb. The distance covered is therefore a significant contribution to the total range. Although climb optimisation can be a complex subject of itself, simplifying procedures are adopted for pilot convenience which aim to achieve the desired cruise altitude as rapidly as possible without too great a compromise on fuel economy. For fighter aircraft the climb schedule normally aimed at is one which maximises the rate of transfer between specific energy levels at constant power. The power setting will be maximum dry power unless a maximum afterburner climb is specifically required, for example over a target area. The appropriate Mach number-Altitude schedule is obtained from the 1 g specific excess power diagram (Fig. 2) and is the locus of optimum specific excess power at constant energy rate, that is where the energy rate (P_s) contours are tangential to those of energy state (E_s). The fuel consumed and range traversed can then be computed by an incremental calculation over the climb to the desired cruise altitude.

The climb appears on the fuel-distance diagram as a curved line reflecting the change in the value of specific range as fuel is consumed.

4.3 Cruise.

Cruising flight may be carried out according to a wide range of speed-altitude schedules depending on the particular mission requirements. It may be desirable to fly at constant speed, constant engine setting or constant altitude. As weight is reduced by consumption of fuel for a constant engine setting, either height or speed or both will increase.

For cruise flight it is normal to adopt certain simplifying assumptions such as zero angle of attack and that the thrust vector acts along the flight path. Since during cruising flight the angle of attack is in fact close to zero these assumptions do not produce significant errors and result in the lift being able to be equated to the aircraft weight and engine thrust, to aircraft drag.

Specific range, that is the distance flown per unit quantity of fuel consumed, is given by the expression:

$$\frac{dR}{dW} = \frac{V}{S.F.C. \times Th} = \frac{1}{W} \cdot \frac{V}{S.F.C.} \cdot \frac{1}{g} \cdot \frac{L}{D}$$

where: R = Range
W = Aircraft mass.
V = Aircraft velocity.
$S.F.C.$ = Propulsion system specific fuel consumption.
Th = Propulsion system thrust.
L = Aircraft lift.
D = Aircraft drag.

The classic 'Breguet' range equation follows from integrating this equation giving: (Ref. 3)

$$R = \frac{V}{S.F.C.} \cdot \frac{1}{g} \cdot \frac{L}{D} \operatorname{Log}_e \frac{W_1}{W_2},$$

where W_1 and W_2 are the aircraft mass at the start and finish respectively of the range increment 'R'. The quantity, $V/S.F.C. \cdot 1/g \cdot L/D$ is termed the range factor (R.F.).

An estimate of the conditions for maximum range can be obtained by computing flight conditions at maximum lift/drag ratio (L/D) for a range of Mach numbers below the critical value, the steep drag rise at this point ensuring that R.F. max. is unlikely to occur at a higher Mach number. The combination of Mach number and altitude which produces the highest range factor for max. (L/D) will be close to the optimum, the remaining influencing factor being the behaviour of the propulsion fuel flow characteristic.

To illustrate this procedure it is convenient to consider a typical drag polar which, over the range of C_L appropriate to cruising flight, can be represented in the parabolic form:

$$C_D = (C_{DO} + \Delta C_{DO}) + KC_L^2 - 2KC_L \,.\, C_L^*$$

where C_{DO} = Zero lift drag coefficient.
ΔC_{DO} = Zero lift drag increment due to external stores.
C_L^* = Lift coefficient at minimum drag.
K = Induced drag factor.

For max. L/D: $\overline{C_L} = (C_{DO}'/K)^{\frac{1}{2}}$

$$\text{and } (L/D)_{\max} = \tfrac{1}{2}\left(\frac{1}{KC_{DO}'}\right)^{\frac{1}{2}}\left(\frac{\overline{C_L}}{\overline{C_L}-C_L^*}\right)$$

where $C_{DO}' = C_{DO} + \Delta C_{DO}$

C_L^* and K are both functions of Mach number and centre of gravity location, but C_{DO} and ΔC_{DO} may be taken as constant below about $M = 0{\cdot}87$.

Since for cruise flight lift may be assumed equal to aircraft weight 'Wg':

$$Wg/\delta = \overline{C_L} \times \gamma/2 \times P_a \times M^2 \times S,$$

where P_a is sea level standard atmospheric pressure.

The altitude is thus defined by the value of δ. Also engine thrust may be assumed to equal aircraft drag such that:

$$Th = \frac{Wg}{(L/D)}.$$

Reference to propulsion part power performance curves gives engine fuel flow 'Wf' as a function of altitude, Mach number and thrust.

Thus, range factor:

$$R.F. = \frac{V}{S.F.C.} \cdot \frac{1}{g} \cdot \frac{L}{D} = \frac{WaM}{Wf}.$$

Because of the influence of forward speed on engine specific fuel consumption a further refinement may be necessary after examining the effect on the range factor of a small change in Mach number at constant altitude. For cruise at a specified altitude the problem is of course considerably simplified.

4.4 High Speed Dash.

A high speed dash is performed at constant altitude and at either a specified throttle setting or a specified Mach number. Where a throttle setting is specified the maximum sustainable Mach

number will correspond to zero energy rate ($P_s = 0$) for unity load factor, except of course where this condition would exceed the allowable structural limit. The Mach number at the appropriate altitude can be obtained from the zero energy rate contour on the specific excess power diagram for the particular throttle setting of interest. The rate of fuel consumption can then be obtained from the propulsion performance data.

Where Mach number and altitude are specified the throttle setting must be determined before fuel consumption can be obtained. As in cruise flight lift can be equated to aircraft weight and for unaccelerated flight, engine thrust is equal to aircraft drag; the required thrust is therefore readily computed and the fuel flow then obtained from the engine part power performance data.

4.5 Combat.

The combat segment of a mission profile may specify numbers of maximum manoeuvre turns or alternatively numbers of turns at a particular altitude, Mach number and power setting. A maximum manoeuvre turn is the maximum sustainable turn rate at a particular energy level. At any energy level (E_s) the maximum turn rate occurs at the load factor (g's) for which the maximum energy rate is equal to zero ($P_s = 0$). Any further increase in turn rate results in negative P_s such that an aircraft experiences a loss of altitude or Mach number or both. However instantaneous turns at negative values of P_s are valid manoeuvres.

The ability of an aircraft to persist in combat can be conveniently quantified by computing the number of 360 degree turns that can be executed at a given radius from base. The number of such turns possible will depend on the aircraft energy level 'E_s' and the fuel available for combat. Figure 4 illustrates how values computed over a range of energy states and radii from base can be presented as a 'Maximum Manoeuvre' diagram.

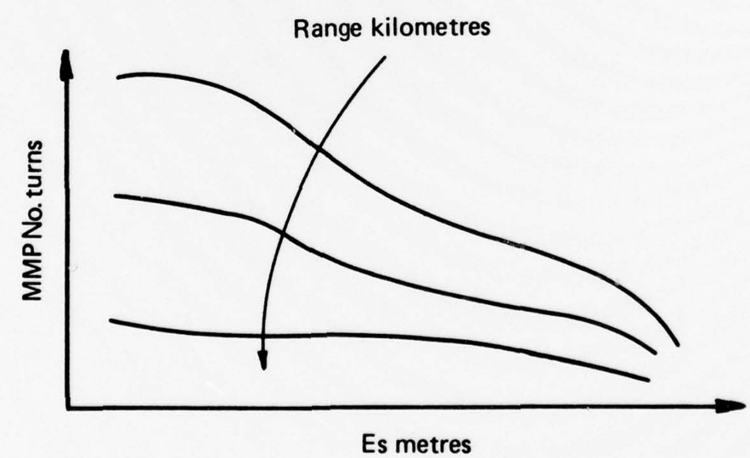

FIG. 4. MAXIMUM MANOEUVRE PERSISTENCE (MMP)

In all types of manoeuvre maximum rate of turn or airspeed may be limited by the airframe structural limits. Specific excess power or energy rate can be computed from the basic aerodynamic and propulsion data to produce a specific excess power diagram at the limiting

load factor, the 'g' limited maximum sustainable turn will be defined by the zero P_s contour on this diagram.

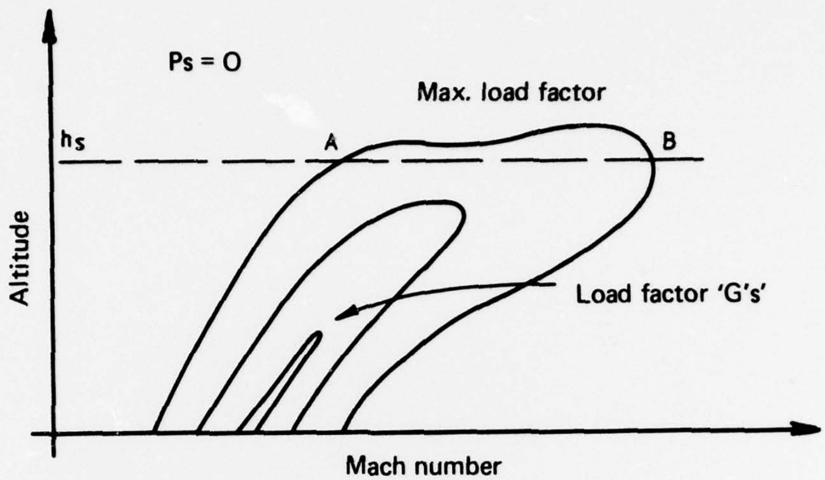

FIG. 5. SUSTAINED MANOEUVRE BOUNDARIES

Figure 5 shows typical sustained load factor boundaries on an altitude, Mach number format. Each contour represents zero specific excess power ($P_s = 0$). A specified altitude for combat persistance ('*hs*' in the figure) will often result in two conditions where energy rate is zero at maximum load factor (*A* and *B*). The lower Mach number value '*A*' will be either on the reverse side of the drag curve where a sharp drag rise accompanies a reduction of speed or is on the lift limited or stall boundary. In either case a speed reduction at constant load factor places the aircraft in a region of negative P_s such that further loss of speed or turn rate results. The higher Mach number at *B* on the other hand is thrust limited and a reduction of speed results in lower drag and possibly higher thrust. This is therefore a stable condition giving the maximum 'g' limited turn rate.

Fuel consumed during combat is a function of throttle setting, altitude and Mach number and is obtained directly from the propulsion characteristics. Since no range is involved in combat manoeuvres this section of a mission will appear on the fuel-distance diagram as a vertical line representing the total fuel consumed during the combat segment. (Figure 1).

4.6 Descent.

In general the data for range and fuel consumption during descent is taken from the aircraft specification performance manual. The chosen height-velocity schedule depends on whether a rapid minimum time descent is required or whether it is desired to maximise range whilst minimising fuel consumption. The aforementioned represent extremes between which approximations such as minimum power at constant descent angle will produce sufficiently accurate estimates of fuel consumption and range traversed.

4.7 Acceleration.

Accelerations are normally specified at constant altitude and throttle setting up to a particular Mach number which may be the maximum permissible airspeed. At any flight condition the value of the specific excess power (P_s) is the measure of the aircraft's ability to accelerate. Since $P_s = V/g.dV/dt$, the value of dV/dt can be determined in a stepwise calculation over the Mach

number range to give the total acceleration time and hence the fuel consumed. The magnitude of the specific excess power is computed for the production of the SEP diagram at the specified throttle setting.

4.8 Loiter.

Loiter at constant altitude involves cruising for maximum endurance which is achieved when $(L/D)/S.F.C.$ is a maximum. As in the previously discussed cruise case, lift may be assumed equal to aircraft weight and thrust equal to aircraft drag. The propulsion system fuel flow is obtained from the part power characteristics.

4.9 Store Drop.

All store drops, including bombs, gun ammunition, missiles and external tanks (when jettisoned), are assumed dropped simultaneously over zero range. This therefore appears on the fuel-distance diagram as a vertical line.

5. CONCLUSIONS

Comparative performance studies of fighter aircraft are considerably enhanced by the production of specific excess power and manoeuvrability diagrams for each aircraft throughout their respective operating envelopes.

Additional performance data, describing specific mission capabilities necessary for the effective comparison of similar aircraft types designed for slightly different roles, often requires a disproportionate amount of further computation. Where a limited number of mission types requires analysis, for example as may occur as part of the selection process involved in the purchase of a new aircraft type, a convenient graphical procedure may be used for mission performance analysis. A large proportion of the data necessary for the production of the graphs is computed as part of the specific excess power calculations.

The graphs, known as 'Fuel-Distance' diagrams, are also a useful illustration of the relative contribution of the various leg components of a complete sortie to the total fuel consumed and distance traversed.

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1. Bird, D. A. H. 'Combat Performance Evaluation of Fighter Aircraft—Principles and Analytical Techniques.' A.R.L./M.E. Report No. 152 October 1978.

2. Kipp, G. W. 'Combat Performance Evaluation of Fighter Aircraft—A Suite of Fortran IV Programs based on Energy Manoeuvrability Theory'. A.R.L./M.E. Report to be published.

3. Page, R. K. 'Range and Radius of Action Performance Prediction for Transport and Combat Aircraft'. AGARD Lecture series No. 56, April 1972.

APPENDIX I

Mission Profiles

The mission performance of an aircraft is usually described by reference to various recognised roles. Each role requires performance excellence in a specialised area such as combat air patrol, or low level strike. A typical definition of performance by role requirements by a prospective customer of a new aircraft type follows:

1. *Air superiority*
   (a) Maximum manoeuvre persistence (MMP), defined as the number of maximum manoeuvre turns which can be performed at a given range from base.

2. *Air Defence*
   (a) The specific intercept range (R_{SI}) at which an aircraft can carry out the following task:
      (i) optimum climb to best cruise altitude;
      (ii) outbound cruise at best cruise speed;
      (iii) 10° descent to 300 m (1000 ft)/450 KIAS (knots indicated airspeed).
      (iv) full afterburner acceleration to 650 KIAS; and
      (v) optimum cruise climb to overhead the departure base with sufficient fuel reserves for 10 minutes holding at cruise altitude.
   (b) The maximum range (MR_L) which an aircraft could achieve in 10 minutes when transitting from its base to the intercept point at 150 m (500 ft) and maximum permissible IAS. Return to base will be via an optimum range profile with 10 minutes holding fuel at cruise altitude overhead the departure base.
   (c) The maximum range (MR_H) at which an intercept could be effected if the aircraft carried out a minimum fuel to energy climb to 12,200 m (40,000 ft)/M1·8, cruised to the intercept at M1·8 and returned to base with 10 minutes holding fuel at cruise altitude.
   (d) The maximum time (MT_I) which an aircraft could spend at *M2·0/16,800 m/(55,000 ft)* on an identification task following a minimum fuel to energy climb to M2·0/16,800 m at a distance of 278 km (150 nm) from base and return to base with 10 minutes holding fuel at cruise altitude.

3. *Interdiction*
   (a) In the absence of any engagement with enemy fighters, the maximum unrefuelled radius of action of an aircraft which uses a high-low-low-high profile. The low level run into and out of the target includes 185 km (100 nm) at 150 m (500 ft)/M0·9.
   (b) In the case of engagement by fighters, the external tanks will be jettisoned and the aircraft returned to the departure base after two minutes combat at full power, M0·9 at 900 m (3,000 ft).

4. *Close Air Support*
   (a) The maximum radius of action when flying a high-low-high profile which requires the aircraft to remain on station for 20 minutes at 1500 m (5,000 ft) followed by 5 minutes at 900 m (3,000 ft) delivering ordnance. Return to base will be via an optimum climb profile with 10 minutes overhead from the departure base at cruise altitude.
   (b) The maximum radius of action when flying a high-low-high profile which requires the aircraft to remain on station for 40 minutes at best endurance altitude followed by 5 minutes at 900 m (3,000 ft) delivering ordnance and an optimal return to base with 10 minutes fuel reserve.
   (c) The maximum radius of action when flying a high level profile which requires the aircraft to remain on station for 40 minutes at best endurance altitude followed by a return to base with all weapons retained and 10 minutes fuel reserve.

(d) The maximum time on station when flying a high level profile which requires that the aircraft fly to a contact point 370 km (200 nm) from base, hold at best endurance altitude, deliver ordnance for 5 minutes at 900 m (3,000 ft) then return to the departure base with 10 minutes fuel reserve.

(e) The maximum time on station when flying a high level profile which requires that the aircraft fly to a contact point 370 km (200 nm) from base, hold at best endurance altitude then return to the departure base with all weapons retained and a fuel reserve of 10 minutes.

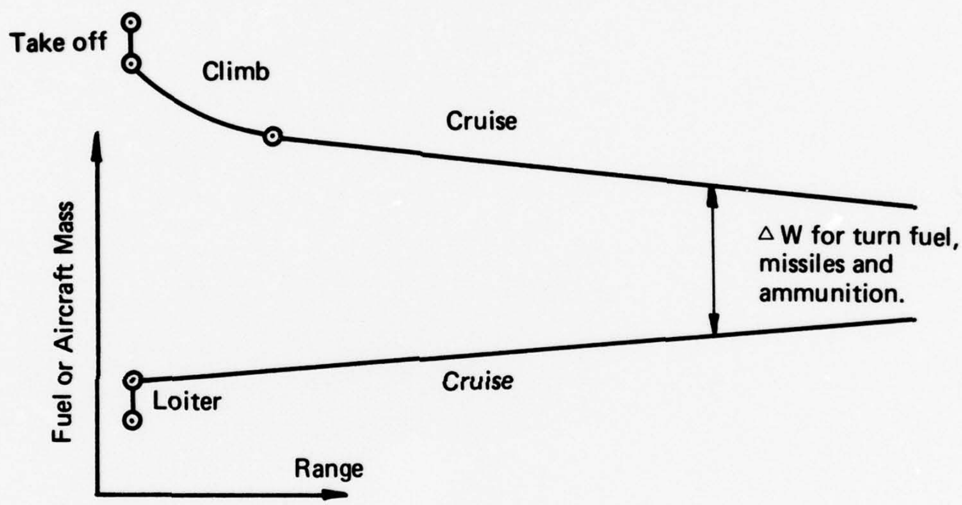
5. *Reconnaissance*

The maximum radius of action when a high-low-low-high profile is flown. The profile requires a 185 km (100 nm) dash into and out of the target at M0·9/150 m (500 ft) and a 10 minute fuel reserve overhead the departure base.

The form of the fuel-distance diagram appropriate to each of these missions is shown below together with a listing of the various component legs and a summary of the derived data.

Air Superiority

Fuel-distance diagram: Maximum Manoeuvre Persistence 'MMP'.

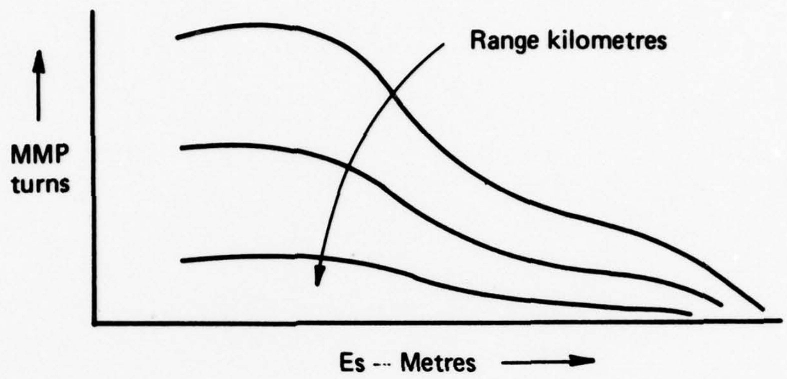


Outward leg commenced at 100% fuel plus all stores.
Climb at military power, optimum energy path.
Cruise performed at optimum altitude and Mach number.
Return leg terminates overhead base with 10 minutes of fuel reserve.
Cruise performed at optimum altitude and Mach number.

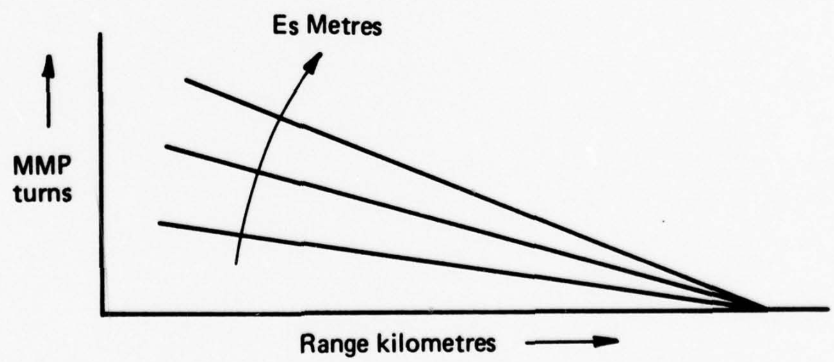
Optimum energy rate calculations give turn rate and fuel flow at various values of 'E_s' and zero 'P_s'. This gives the maximum sustained turn rate at maximum power and specified 'E_s' and mass.

Hence fuel consumed or loss of mass per 360° turn can be computed and the radius at which '*n*' such turns can be performed obtained graphically from the range wedge.

(i) MMP displayed as function of E_s for constant ranges.

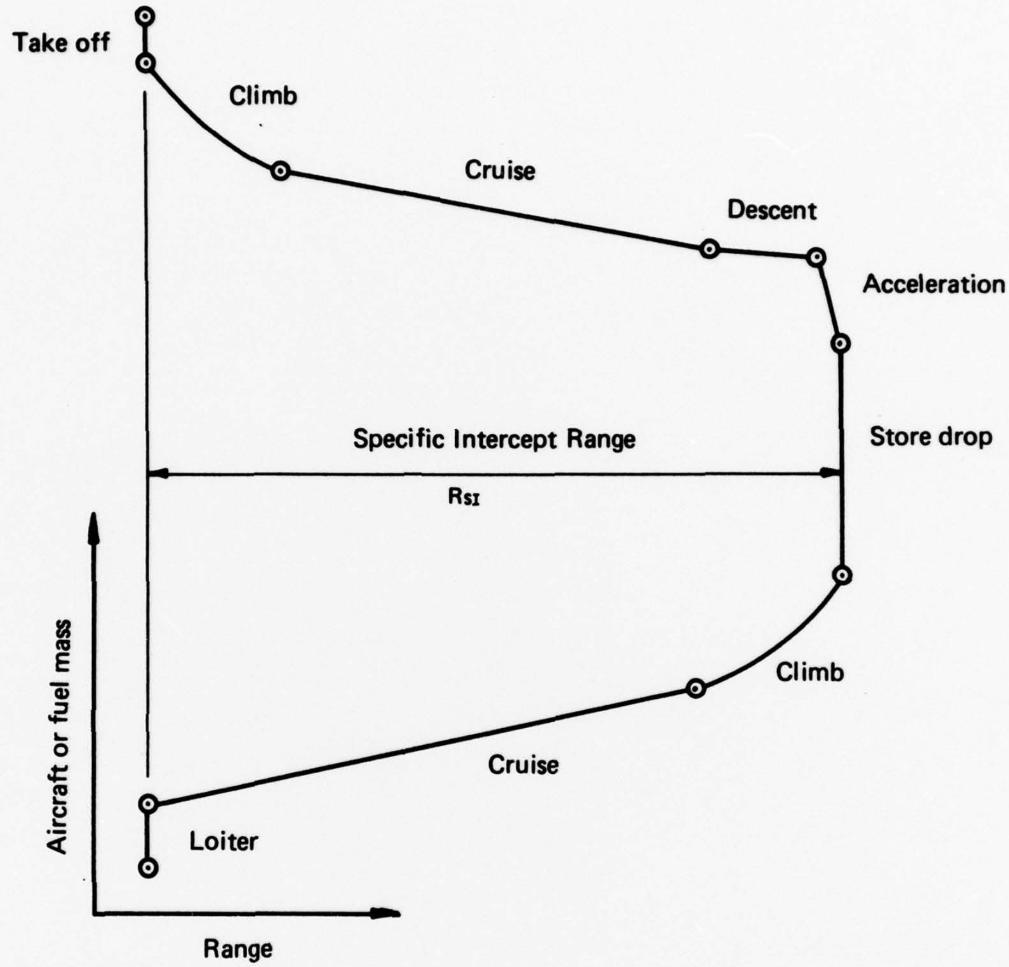


(ii) MMP displayed as a function of range for constant E_s.



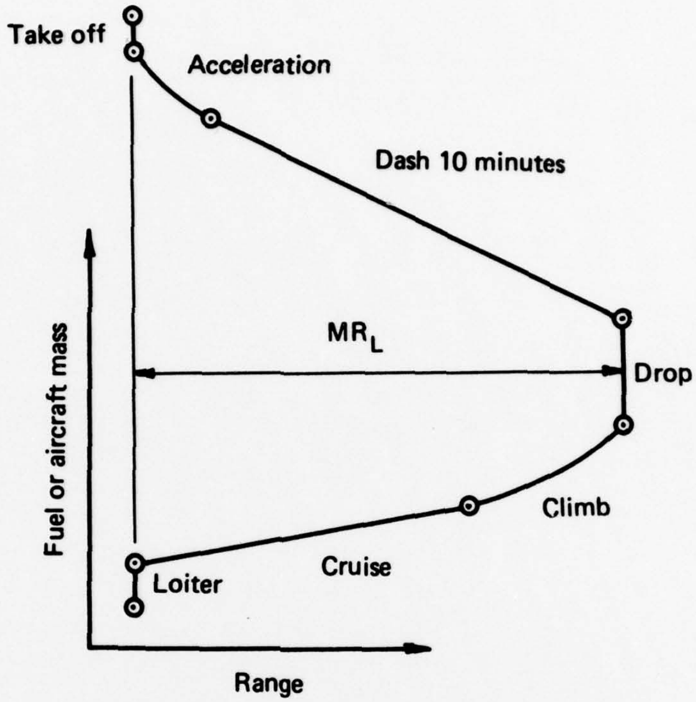
Air Defence

(a) Fuel-distance diagram: Specific Intercept Range 'R_{SI}'.



Outward leg commenced at 100% fuel plus all stores.
Climb at military power optimum energy path.
Cruise performed at optimum altitude and Mach number.
Descend at 10° to 300 m (1000 feet) and 450 KIAS (M0·692).
Acceleration at 300 m at maximum afterburner to 650 KIAS (M0·998).
Stores dropped and gun fired at end of acceleration.
Return climb at military power optimum energy path.
Cruise at optimum altitude and Mach number.
Specific intercept range (R_{SI}) obtained from range wedge at point at which stores are dropped.

(b) Fuel-distance diagram: low altitude intercept 'MR_L'.



Outward leg commenced at 100% fuel plus all stores.

Acceleration at maximum afterburner to maximum permissible I.A.S. at 150 m (500 ft) altitude.

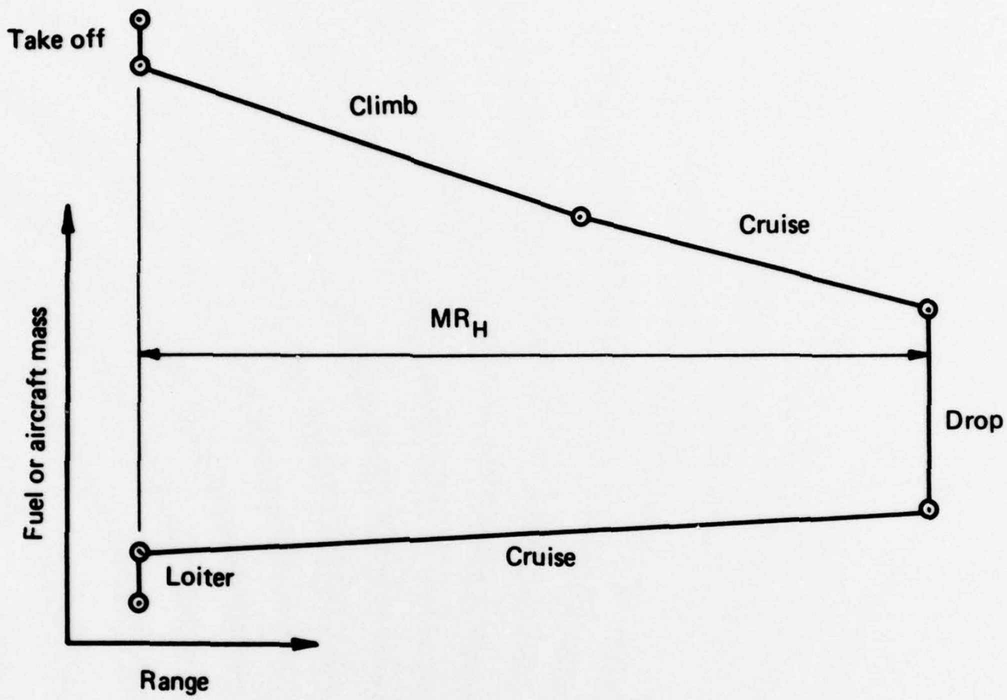
Cruise at maximum I.A.S. for 10 minutes and drop stores.

Return climb at military power optimum energy path.

Cruise return at optimum altitude and Mach number.

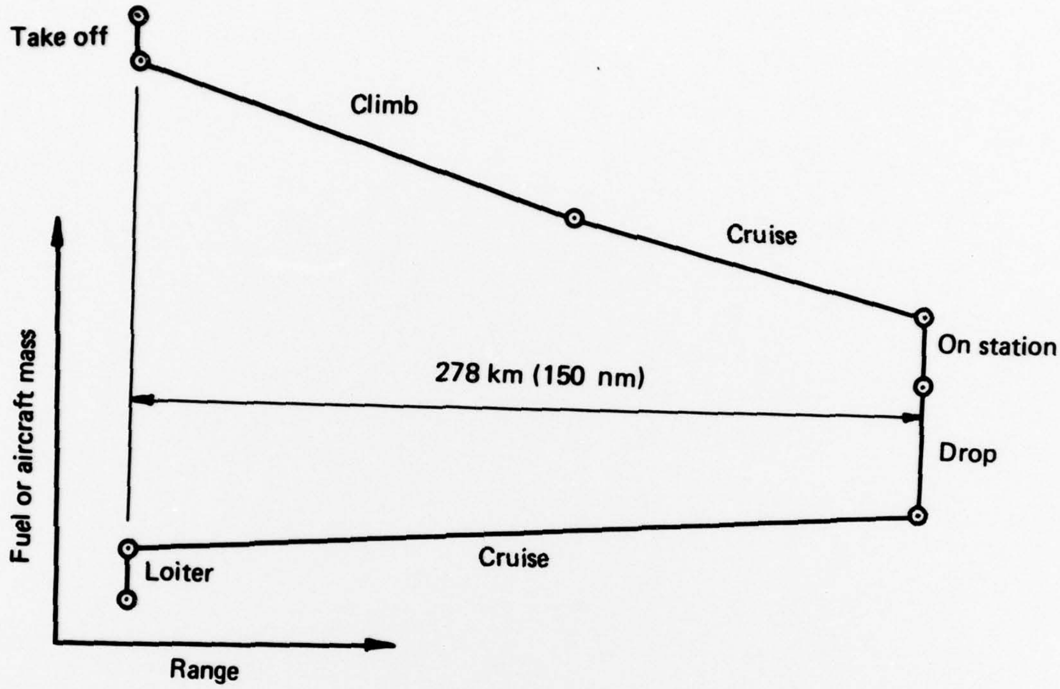
Maximum range obtained from range wedge, note that dash may not last 10 minutes depending on return leg requirements.

(c) Fuel distance diagram: high altitude intercept 'MR_H'.



Outward leg commenced at 100% fuel plus all stores.
Climb at mil./max. afterburner min. fuel schedule to 12,200 m (40, 000ft), M1·8.
Cruise at M1·8/12,200 m until stores dropped.
Return cruise at mil. power optimum altitude and Mach number.
Maximum range obtained from range wedge, note that 12,200 m/M1·8 may not be attainable before necessity to drop stores and return to base.

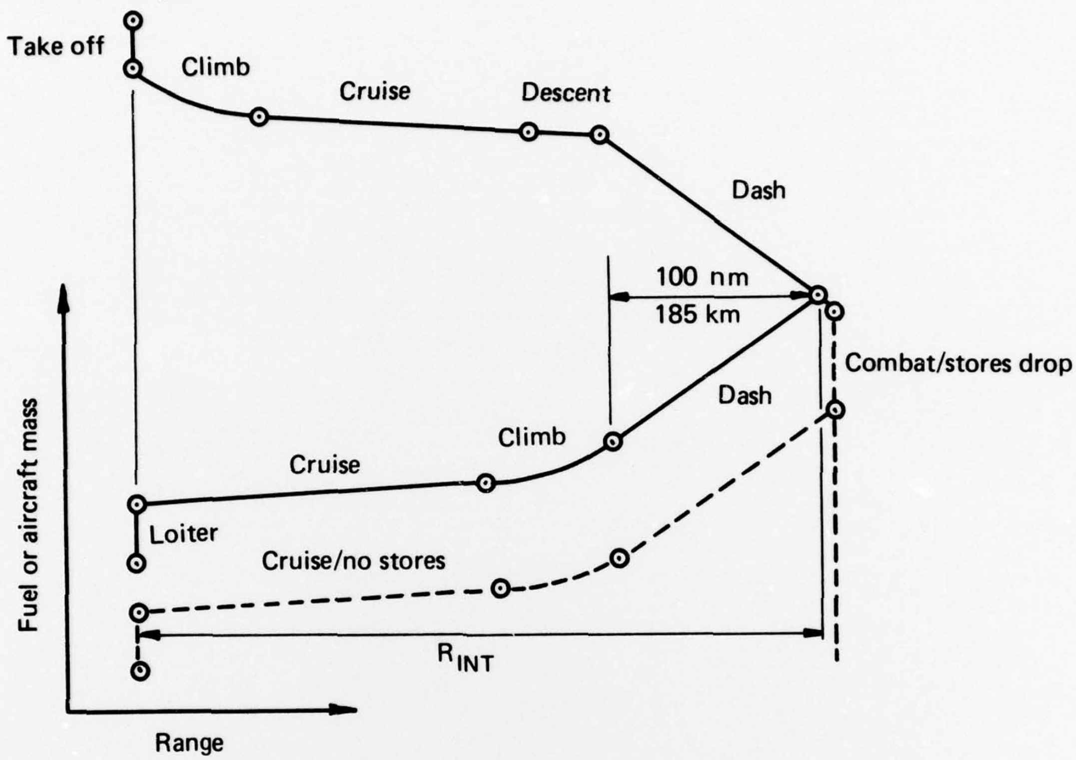
(d) Fuel-distance diagram: high level identification.



Outward leg commenced at 100% fuel plus all stores.
Climb mil./max. afterburner min. fuel to M2·0 and 16,800 m (55,000 ft).
Cruise at M2/16,800 m to 278 km from base, remain on station at M2/16,800 m.
Drop stores and return at optimum altitude and Mach number.
Maximum time (MT_I) is time to consume allowable mass loss in fuel at M2/16,800 m.
Mass loss on station obtained from range wedge.

Interdiction

Fuel-distance diagram:



Outward leg commenced at 100% fuel plus stores.

Climb is military power optimum energy path.

Outward cruise at optimum altitude and Mach number.

Descent at 10° to 150 m (500 ft).

Dash at 150 m/M0·9 for 185 km (100 nm).

If enemy engaged, external tank is dropped and 2 minutes of combat at 900 m/M0·9 is allowed for at max. power.

Return dash at 150 m/M0·9 for 185 km.

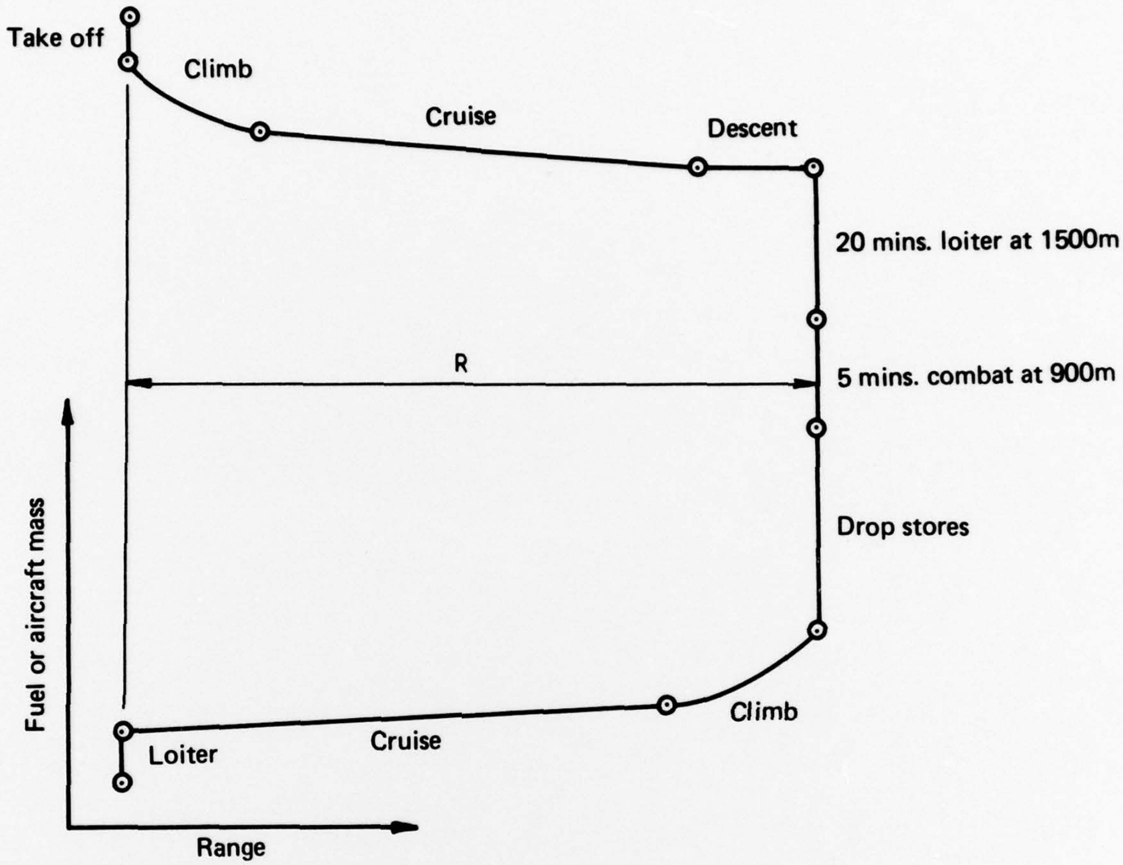
Climb at military power minimum time to energy.

Cruise return at optimum altitude and Mach number.

Interdiction range with or without enemy engagement obtained from range wedge and includes the 185 km dash into and out of the target.

Close Air Support

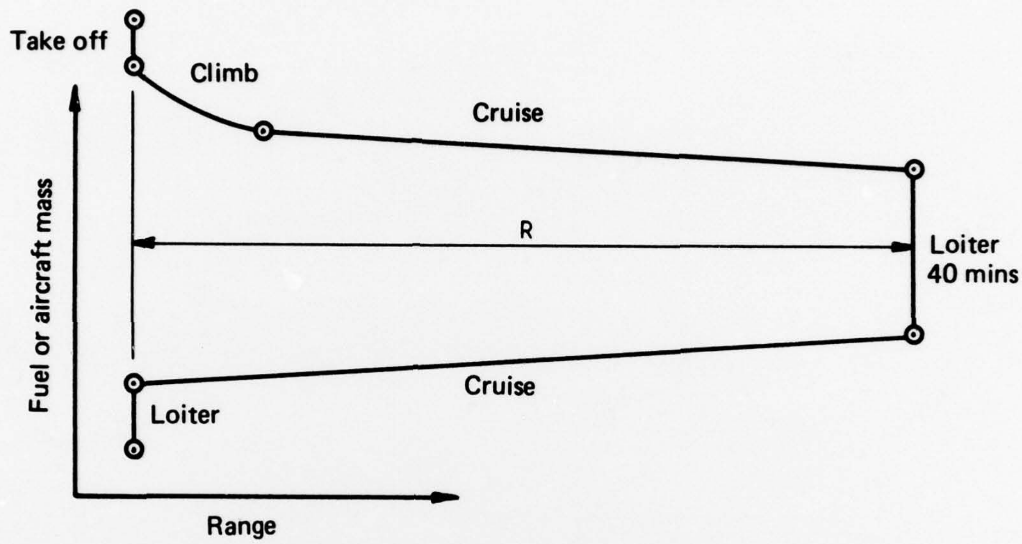
(a) Fuel-distance diagram: 1500 m (5000 ft) loiter.



Outward leg commenced at 100% fuel plus all stores.
Climb out at military power optimum energy path.
Cruise at optimum altitude and Mach number.
Descend at 10° to 1500 m (5000 feet) altitude.
Loiter at 1500 m for 20 minutes.
Descend to 900 m, assume zero fuel and time.
Five minutes combat at 900 m, mil. power maximum turn rate at $P_s = 0$, followed by store drop.
Return climb at military power optimum energy path.
Cruise at optimum altitude and Mach number.
Range required is that at loiter and combat.

(b) Loiter at cruise altitude.
Profile as for part (a) but loiter performed at end of outward cruise for 40 minutes. Descent to 900 m follows for 5 minutes combat and store drop.

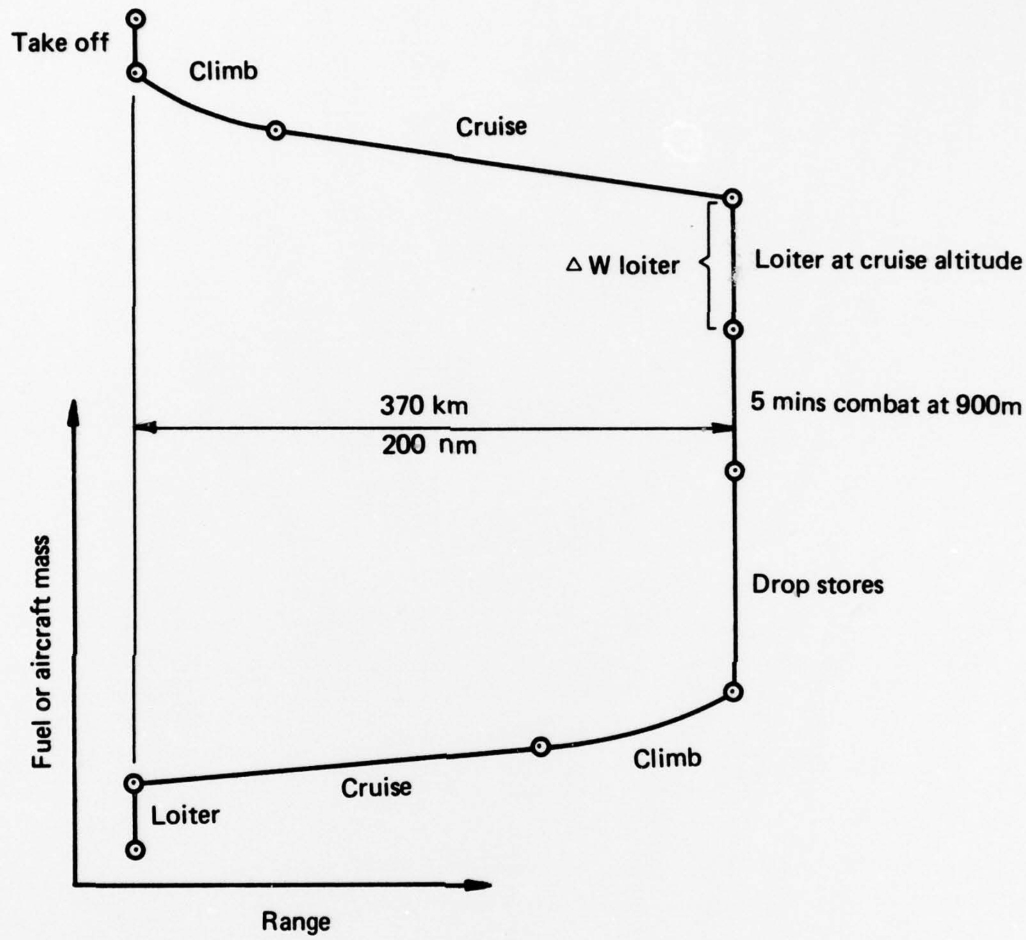
(c) Fuel-distance diagram: high level profile.



As (b) above with return cruise at optimum altitude and Mach number following loiter over target.

All weapons retained for return to base.

(d) Fuel-distance diagram: time on station.

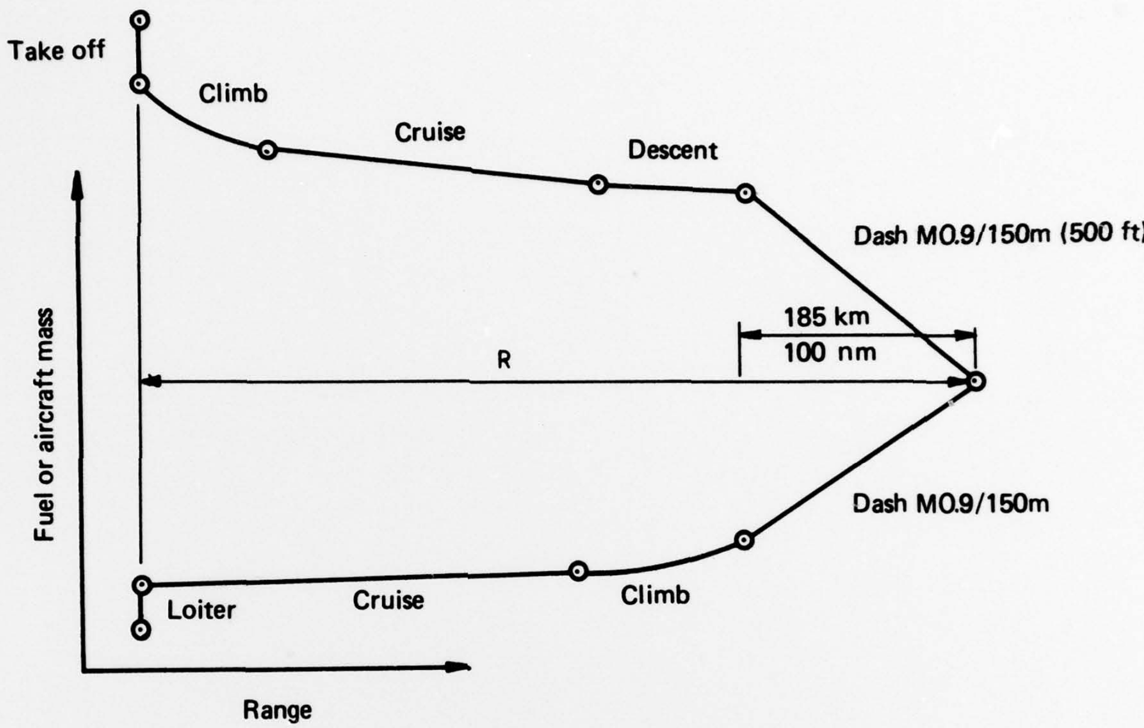


As item (b) above but outward cruise terminated at 370 km radius.
Required to know time to loiter on station at cruise altitude to consume available ΔWkg fuel.

(c) Time on station no combat.
As (c) above but outward cruise terminated at 370 km.
Require to know time to loiter on station at cruise altitude to consume available ΔWkg fuel.

Reconnaissance.

Fuel-distance diagram:



Outward leg commenced at 100% fuel plus stores.
Climb is military power optimum energy path.
Outward cruise at optimum altitude and Mach number.
Descent at 10° to 150 m (500 ft).
Dash at M0·9 for 185 km (100 nm).
Return dash at M0·9/150 m for 185 km.
Military power climb by optimum energy path.
Return cruise at optimum altitude and Mach number.
Required to know range at end of 185 km dash.

APPENDIX II

Example Calculation

Mission: Close Air Support.
Configuration: 2 Air to air missiles, Gun plus full ammunition, 6 Bombs on external pods.

Mass at take off = 12,250 kg (27 000 lbs) including:
Air to air missiles 2 × 73 kg (320 lbs)
Ammunition 127 kg (280 lbs)
Six bombs 6 × 227 kg bombs (3000 lbs)
Total jettisonable store mass = 1635 kg (3600 lbs)
Total fuel mass at take off = 2950 kg (6500 lbs)

Take Off:
Aircraft flight manual:
Configuration drag index = 245 drag counts ($\Delta C_{DO} = 0 \cdot 0245$)
Ground taxi fuel consumed = 159 kg (350 lbs)
Take off to 300 m (1000 ft)
Fuel = 227 kg (500 lbs)

Total = 386 kg (850 lbs) ←
Range = 11 km (6 nm) ←

Outward Climb:
Maximum Manoeuvre calculations give:

Altitude m (ft)	Fuel consumed kg (lbs)	Range km (nm)
0	0	0
900 (3000)	82 (180)	11 (6)
5000 (16000)	363 (800)	65 (35)
9000 (30000)	1134 (2500)	296 (160)

A plot of this sample and intermediate values shows that for climb commencing at 300 m (1000 ft); 12 kg (40 lbs) fuel and 3·7 km (2 nm) range should be subtracted from the above values.

Outward Cruise:
Estimated mass at end of climb = 10900 kg (24000 lbs).
Calculations give:

M	$\overline{C_L}$	$(L/D)_{max}$	h metres (ft)	Thrust-N (lbs)
0·80	0·2885	6·951	10 670 (35 000)	14 900 (3350)
0·84	0·2930	6·821	11 400 (37 400)	15 100 (3400)

Say the engine will not provide this thrust at maximum dry power so further calculations at lower altitudes and non-optimum L/D give;

M	C_L	L/D	h metres (ft)	Thrust-N (lbs)	R.F.-km (nm)
0·83	0·2080	6·405	9000 (29 500)	16 460 (3700)	4630 (2500)

Return Cruise:

The return cruise is computed at this stage to enable the range wedge to be constructed graphically.

Mass empty = 7575 kg (16 700 lbs)

Calculations give:

M	C_L	$(L/D)_{max}$	h-m (ft)	Th-N (lbs)	R.F.-km (nm)
0·85	0·2204	8·046	12 000 (39 600)	9016 (2027)	6106 (3297)
0·87	0·2208	8·011	12 400 (40 600)	9052 (2035)	6182 (3338) ←
0·89	0·2228	7·915	12 700 (41 800)	9163 (2060)	6141 (3316)

Further considering 12 400 m alt.

M	C_L	C_{DO}	Th-N (lbs)	Wf-kg/s (lbs/hr)	R.F.-km (nm)
0·85	0·2313	0·0288	9029 (2030)	0·3077 (2442)	6030 (3256)
0·89	0·2109	0·0267	9176 (2063)	0·3121 (2477)	6225 (3361) ←
0·91	0·2018	0·0262	9412 (2116)	0·3219 (2555)	6169 (3331)

Loiter over base:

Maximum endurance at cruise altitude is achieved at the cruise Mach number.

10 minutes loiter; Wf = 0·3121 kg/s (2477 lbs/hr)

ΔW = 187 kg (413 lbs) ←

Thus the aircraft mass at the end of the return cruise will be 7575 + 187 = 7762 kg (17112 lbs)←

The outward and return cruise legs of the mission are now drawn graphically to form the range wedge.

Descent:

The fuel consumed and range covered during descent to 1500 metres from cruise altitude is given in the performance manual.

The figures are: ΔW = 45 kg (100 lbs) ΔR = 37 km (20 nm) ←

Loiter at 1500 m altitude.

An estimate of the mass must be made for this computation and the 50% fuel condition is normally taken. $W \simeq$ 10 433 kg (23 000 lbs).

Computations give for $[(L/D)/S.F.C.]$maximum;

M = 0·4, Th = 15 570 N (3500 lbs), Wf = 0·58 kg/s (4600 lbs/hr).

For 20 minutes loiter: ΔW = 695 kg (1533 lbs) ←

Combat at 900 m (3000 ft).

Descent from 1500 m to 900 m is assumed to consume no fuel.

Military power optimum turn rate data is obtained from specific excess power optimisation for the maximum manoeuvre diagram: $M \simeq 0{\cdot}69$, Wf = 1·36 kg/s (10 800 lbs/hr)

For 5 minutes combat: ΔW = 408 kg (900 lbs) ←

Return Climb:

The estimate of the aircraft mass at the commencement of the return climb follows from the estimate at 1500 metre loiter minus the subsequent mass losses including the store drop of 1635 kg.

Maximum Manoeuvre calculations give:

Altitude metres (ft)	Fuel consumed kg (lbs)	Range km (nm)
0	0	0
1500 (5000)	87 (192)	15 (8)
5200 (17 000)	215 (475)	43 (23)
9750 (32 000)	362 (799)	93 (50)

A plot shows that for climb from 900 m; 63·5 kg fuel and 10·2 km range should be subtracted from these values.

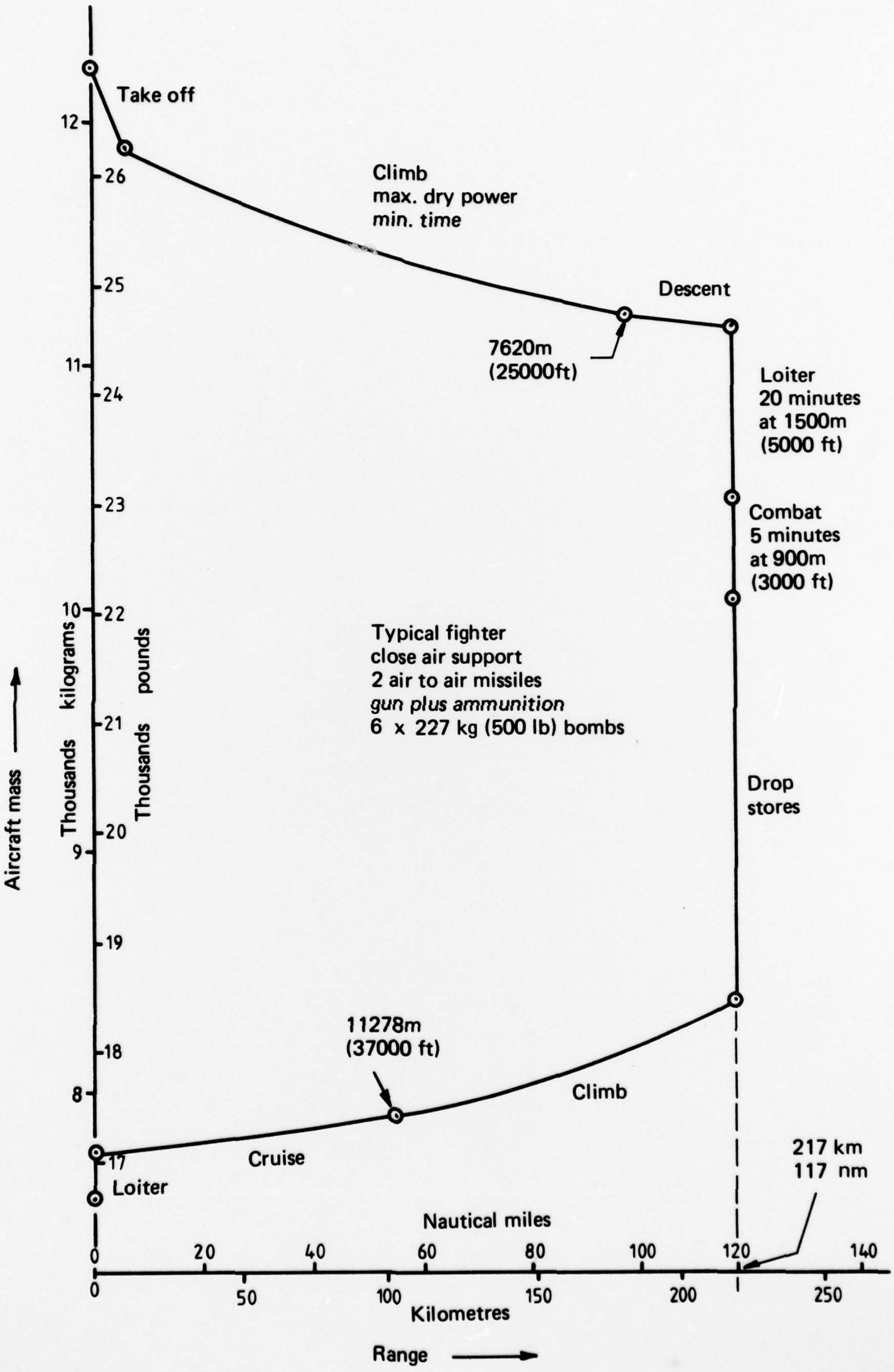
The vectors representing the descent, loiter at 1500 m, combat at 900 m, store drop and

return climb, are next constructed in sequence on the fuel-distance diagram so as to fit between the outward and return cruise vectors.

In this example reference to Figure 1 shows that the descent must be commenced before the outward cruise altitude is reached. Also the return climb to cruise altitude cannot be achieved before the aircraft approaches base. The return climb has been terminated at a lower altitude and cruise commenced at the optimum Mach number for cruise at that altitude. This is the result of investigating a range of alternative cruise altitudes below the optimum to minimise the total fuel consumed during the return climb and cruise legs.

The range figure finaly obtained from the diagram is 217 kilometres (117 nautical miles).

FIG. 2.1


Take off
Climb
max. dry power
min. time
Descent
7620m
(25000ft)
Loiter
20 minutes
at 1500m
(5000 ft)
Combat
5 minutes
at 900m
(3000 ft)
Typical fighter
close air support
2 air to air missiles
gun plus ammunition
6 x 227 kg (500 lb) bombs
Drop
stores
11278m
(37000 ft)
Climb
Cruise
Loiter
217 km
117 nm
Aircraft mass
Thousands kilograms
Thousands pounds
12
11
10
9
8
26
25
24
23
22
21
20
19
18
17
Nautical miles
0
20
40
60
80
100
120
140
0
50
100
150
200
250
Kilometres
Range

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ABSTRACT

Comparative studies of aircraft performance, undertaken to assess the relative merits of similar types, will necessarily entail not only a detailed qualitative assessment of dynamic performance but also a measure of each machine's ability to carry out specific missions.

Energy manoeuvrability theory can be used to provide specific excess power and turn capability of an aircraft throughout its operating envelope. The various manoeuvres comprising a complete mission can then be optimized from this data and a convenient graphical method employed to analyse the mission performance.

In this technique each leg of a sortie is represented on a Fuel-Distance diagram as fuel weight consumed versus range traversed. The resulting diagram serves both as a convenient illustration of the relative contribution of each leg to the total fuel consumed and range traversed over a complete mission, and also as a simple method of determining the total operational radius of action or duration on station.

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